Hybrid multi-grids simulations of Ganymede's magnetosphere

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1- Abstract

Ganymede is a unique object :

- **Biggest moon** of our solar system
- Only satellite which has its own **intrinsic magnetic field** leading to the formation of a **small magnetosphere**
- Magnetosphere of Ganymede is **embedded in the Jovian magnetosphere :** only known case of interaction between
- two magnetospheres (Kivelson et al. 1996).
- Formation of **Alfvèn wings**

Interaction modeled by a 3D parallel multi-species hybrid model based on a CAM-CL algorithm (Mathews et al. 1994) :

- **Generic model** applied to Mars (Modolo et al. 2005; 2006 and 2012), Titan (Modolo et al. 2007, Modolo and Chauteur 2008) or Mercury (Richer et al. 2012).
- **Maxwell's equations** are solved to compute the temporal evolution of electromagnetic field.
- Description of the the dynamics of the magnetospheric plasma and Ganymede's ionospheric plasma
- Simulations results are presented and compared to magnetometer and particle observations obtained during G1 and G2 Galileo flybys.

2- Description of the model

Hybrid formalism :

- Ions have a **kinetic description** and are represented by **macroparticles** that have a mass, a charge and a weight (=number of physical particles that represents the macroparticle)
- e^- described as an **inertialess fluid** to ensure the **quasi-neutrality** of the plasma. Represented by a **Maxwelian distribution.**

Maxwell's equations used in the model :

$\nabla . B = 0$ (1) Conservation magnetic flux equation

$\nabla \times E = \frac{-\partial B}{\partial t}$ (2) Faraday's equation

$\nabla \times B = \mu_0 (J_e + J_i) + \cancel{\mu_0 \varepsilon_0 \frac{\partial E}{\partial t}}$ (3) Ampere's equation

Negligible since we consider only low frequencies phenomena

Motion of the ions :

$$\frac{dv_s}{dt} = \frac{q_s}{m_s}(E + v_s \times B)$$

$$\frac{dx_s}{dt} = v_s$$

Electron momentum equation :

$$n_e m_e \frac{du_e}{dt} = 0 = -e n_e (E + u_e \times B) - \nabla . \overline{\overline{P_e}} \quad (4)$$

(4)+(3) = $$E = \frac{-J \times B}{\rho} + \frac{(\nabla \times B) \times B}{\mu_0 \rho} - \frac{\nabla p_e}{\rho}$$

Numerical model :

- **C**urrent **A**dvance **M**ethod and **C**yclic **L**eapfrog (CAM-CL)
- Matthews et al. 1994
- Considerable reduction of time computation
- Multiple ion species treated with **only one pass** through the
- particle data

- Ions : Motion equations integrated with a **leapfrog scheme**
- The model is parallelized with MPI (Message Passing Interface) thanks to domain decomposition methods

3- Ingredients of the model

Incident plasma parameters (from G1 flyby) :

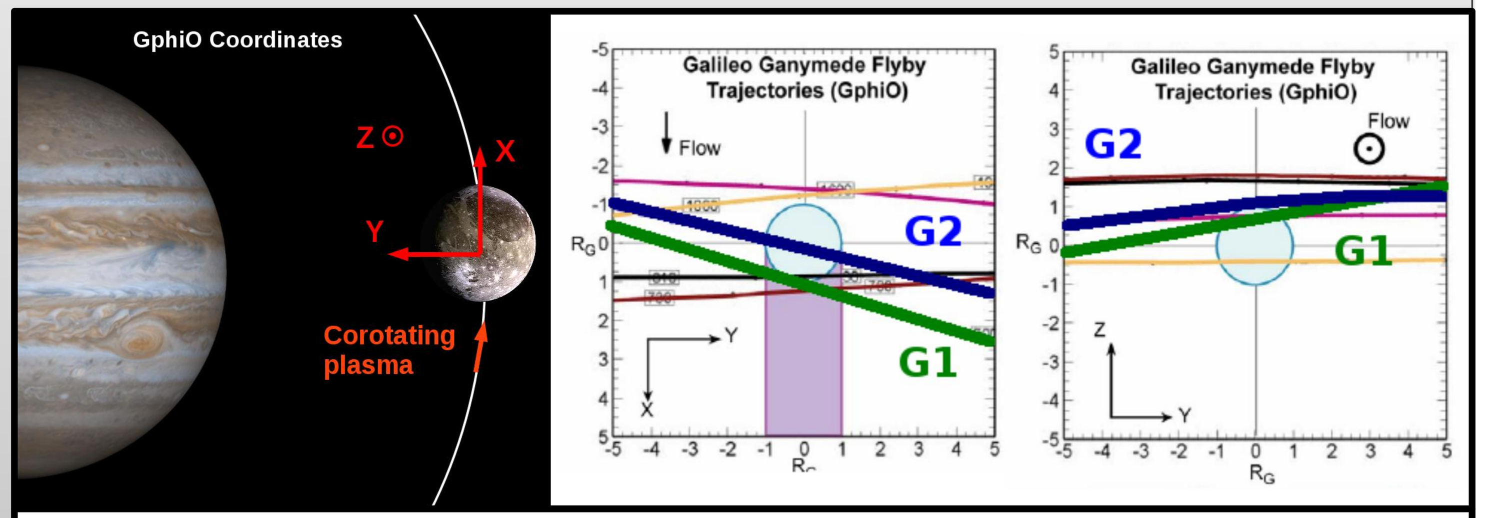
- Flow velocity : 140km/s (Williams et al. 1997)
- Electron density : 4cm^{-3} (Galileo PWS, Gurnett et al. 1996)
- 2 ion species : O^+(3,47cm^{-3}) and H^+(0,53cm^{-3}) (Kivelson et al. 2006 ; Cooper et al. 2001)
- Jovian magnetic field (KK97 model, Khurana, 1997) B=(0,-79,-79) nT

Ganymede's ionosphere :

- O^+ (5000cm^{-3} at the surface, from our hypothesis)
- H=125km (Paty and Winglee 2004)

Ganymede's magnetosphere :

- About 720 nT at the equator (Kivelson et al. 2002)
- Magnetic dipole implemented at initialization distortion leading to the formation of a magnetosphere



Gphio Coordinates | G1 : closest approach about 830km | G2 : closest approach about 240 km

4- Numerical parameters

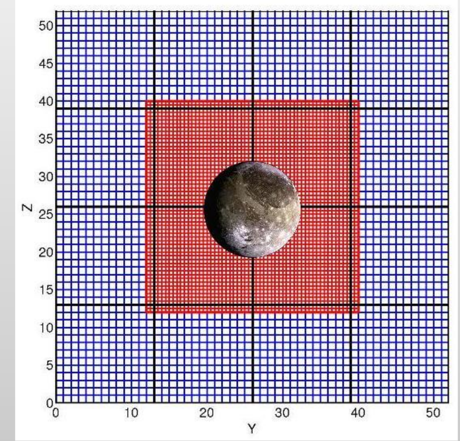
- Fields and particle moments computed on a cartesian grid
- Simulation box size : -12 R_G<X<6 R_G ; -18 R_G<Y<18 R_G ; -27 R_G<Z<27 R_G

2 runs :

1) Uniform grid - Δx=240 km

2) Multi-grids - Δx=120 km at close vicinity of Ganymede (6,3 R_G×11 R_G×11 R_G) - 240 km elsewhere

- Jovian plasma : 10 macroparticles/cell
- Ionosphere :
- Simulation time = 200 O^+ gyromotions ; dt=0.005Ω^{-1}_{O+} 256 CPUs – Restitution time about 9,5 days



Multi-grids method described in Leclercq et al., JCP, 2015

5- Results

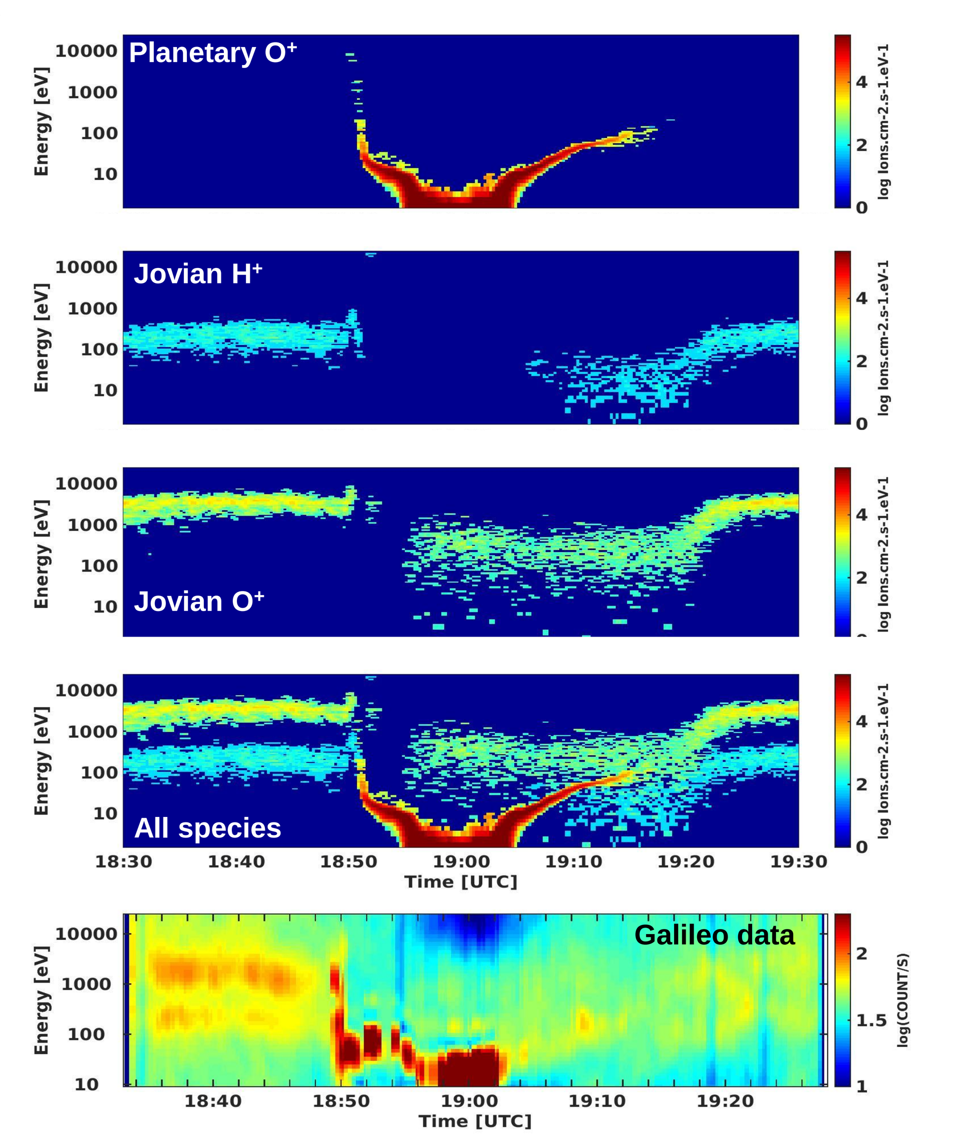
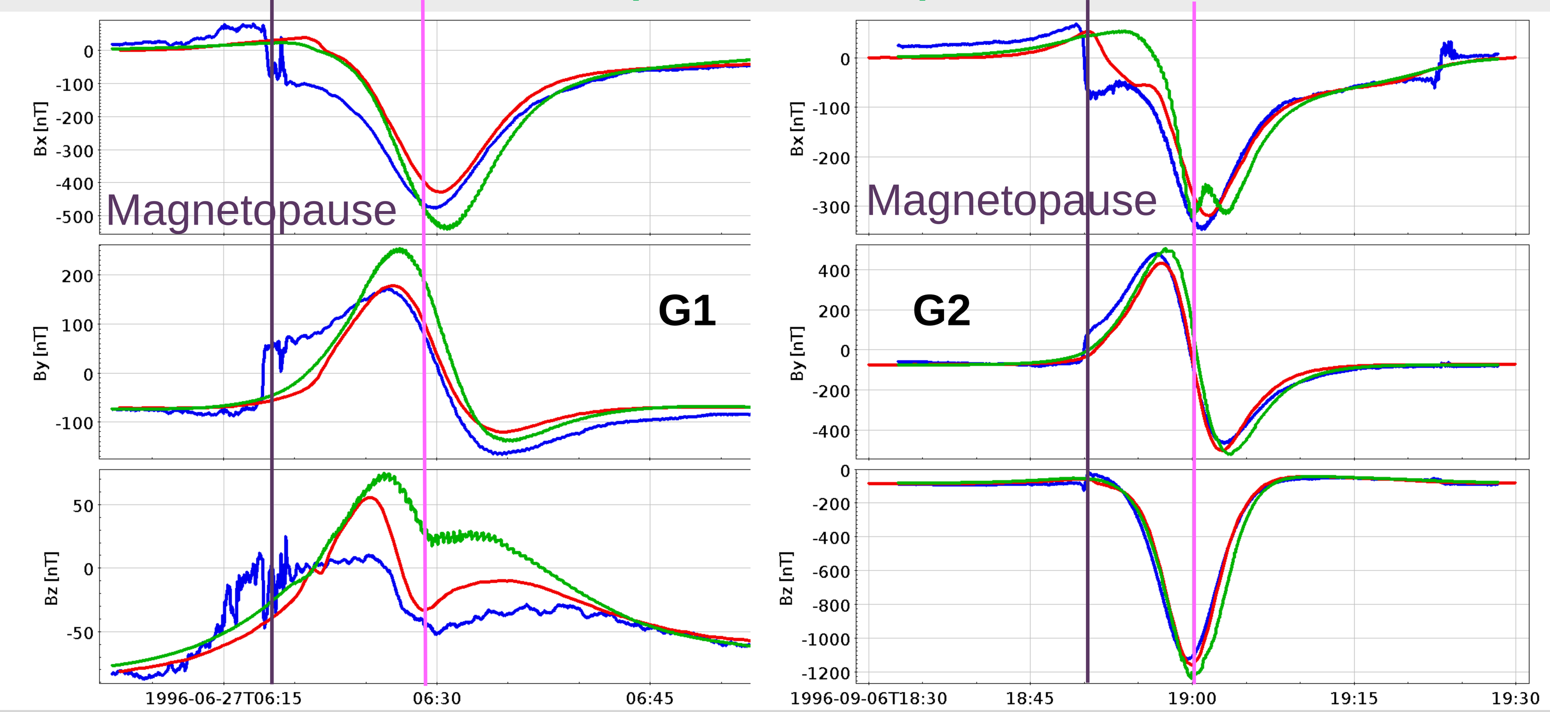


Figure 1: Ion energy spectra during G2 flyby. Bottom: Galileo measurements. Top: Different species of our simulation (RUN 2)

Figure 2: Magnetic field measured (in blue) per Galileo, and simulated (RUN 1 / RUN 2)



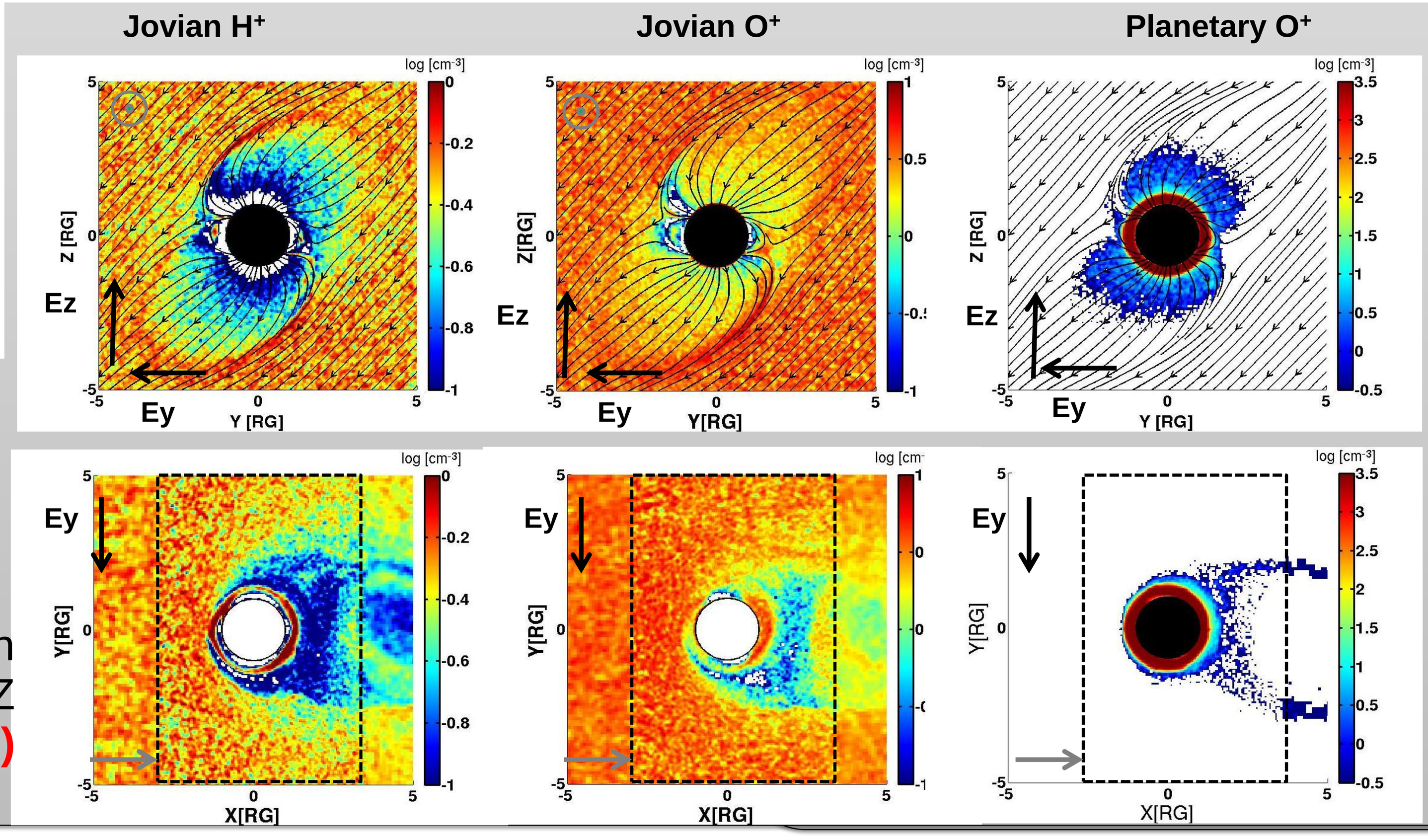


Figure 3: Densities of Jovian H+ (left), Jovian O+ (middle) and Planetary O+ (right) in the YZ (top) and XY (bottom) planes (RUN 2)

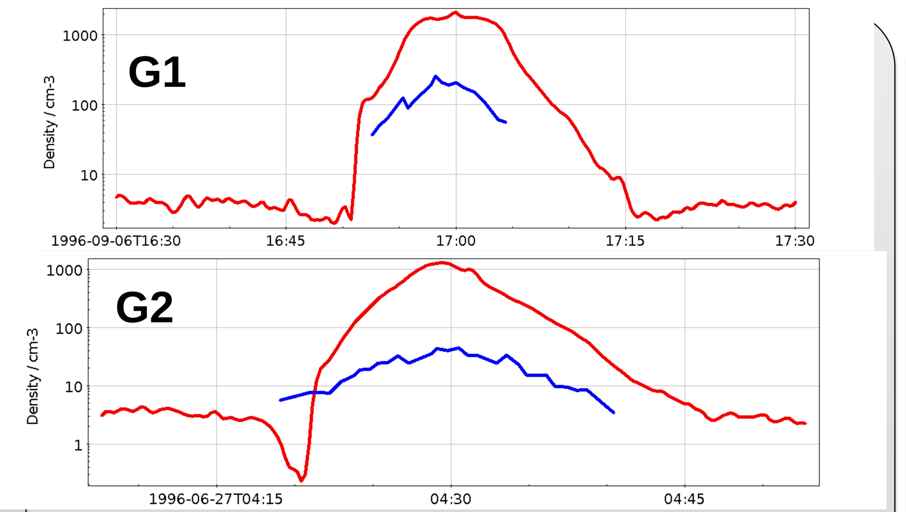


Figure 4: Electron densityalong G1 (bottom) and G2 (top) trajectories. Observations in blue and simulation in red (RUN 2)

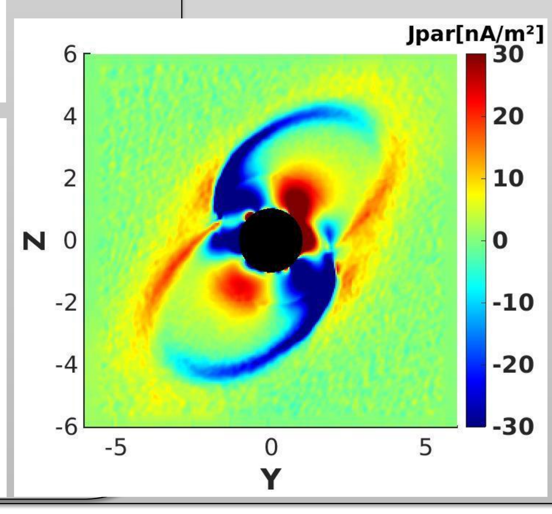


Figure 5: Simulated parallel currents in the YZ plane

6- Conclusions and perspectives

Conclusions:

- Importance of kinetic effets (ion gyromotion)
- Importance of the multi-species aspect
- Results improved by spatial resolution refinement
- Good agreement between our model and Galileo measurements

Perspectives:

- Add species in the ionosphere
- Add charge exchange reactions, photoproduction, electron impact ionization
- Compute ion precipitating flux at surface
- Couple with our 3D multi-species parallel exospheric model based on Monte Carlo methods (Turc et al., 2014). See Figure 6.
- Couple with our ionospheric model (Leblanc et al., in prep). See Figure 7.

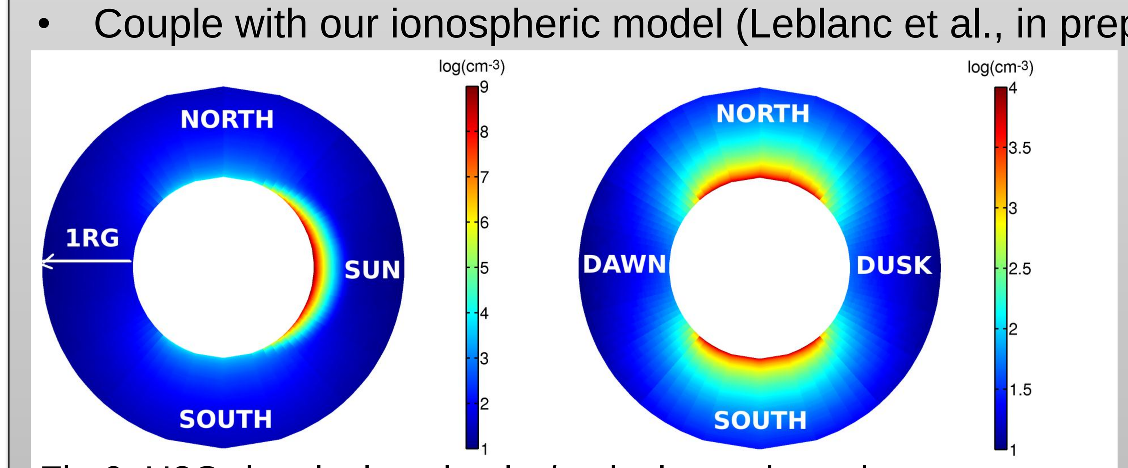


Fig 6: H2O density in subsolar/antisolar and terminator planes

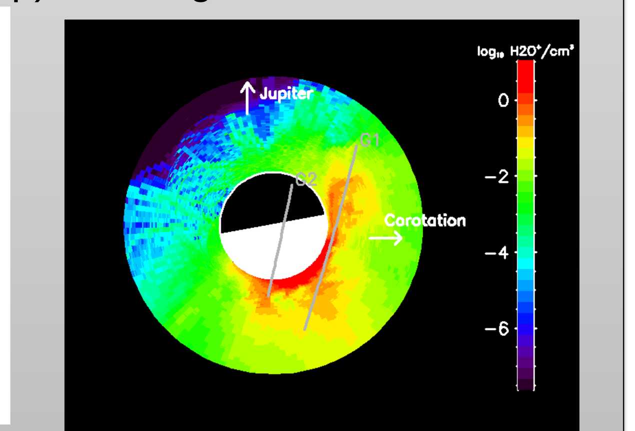


Fig 7: H2O density in equatorial plane